PHOSPHORUS REMOVAL AND WATER QUALITY IMPROVEMENTS IN GRAVENHURST BAY, ONTARIO

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Ministry of the Environment

The Honourable William G. Newman, Minister

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75

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TABLE OF CONTENTS

SUMMARY AND CONCLUSIONS

Gravenhurst Bay, part of a soft-water lake system in Ontario's Precambrian Shield has been affected by phosphorus loadings of 2.37 g $P/m^2/yr$, resulting mainly from municipal sewage discharges. In August of 1971, improved treatment at waste treatment plants reduced the loading of phosphorus to 0.40 g $P/m^2/yr$. Since that time there have been a number of limnological responses toward improved water quality.

Euphotic zone average total phosphorus concentrations decreased from 43 to 30 μg/l and the minimum summer values decreased from 20 to 10 μg/l before and after phosphorus reduction, respectively.

Phytoplankton biomass decreased from a pre-removal 3-year average of 2700 a.s.u./ml to a 1400 a.s.u./ml 3-year average since 1971. Correspondingly, water clarity increased 16% and chlorophyll _a_ concentrations decreased 38%. Phytoplankton species such as _Dinobryon_ spp., _Chroococcus_ spp. and _Synura_ spp. indicative of less enriched waters have appeared since 1971. Occasional "water-blooms" owing to the blue-green algae _Aphanizomenon flos-aquae_ and _Anabaena flos-aquae_ observed in past years have been absent since the P removal programme was initiated.

As a result of reduced phytoplankton biomass and presumably decreased production, maximum pH values decreased from 9.0 prior to 1972 to 8.0 in 1974. Carbon dioxide which was completely depleted in the surface waters prior to 1972 has remained near 1 mg/l throughout the summers of 1972, 1973 and 1974. Inorganic nitrogen followed the same trend, averaging 64-84 μg N/l prior to phosphorus reduction and 135-185 μg/l since 1971, suggesting decreased rates of demand by phytoplankton which is now P limited.

The Gravenhurst Bay case is the first instance in Ontario where field studies have confirmed, at least in the short term, the validity of earlier predictions (Michalski et _al_. 1973; Brydges 1971). As a result, the Province's phosphorus removal programme can be viewed with a certain amount of optimism.

INTRODUCTION

Limnological investigations designed to define improvements in surface water quality following reduced artificial loadings of phosphorus have been few. Notable exceptions include case histories of the Zellersee in Austria (Liepolt 1966), Lake Norrviken in Sweden (Ahlgren 1972), Lake Washington in the United Stated (Edmondson 1970 and 1972), and Little Otter Lake in Ontario (Michalski and Conroy 1973). As waste management practices are being upgraded in several regions of Canada and the United States, efforts by aquatic scientists have been directed towards assessing changes in the quality of receiving waters. To this end, limnological data are being collected on several lakes now receiving or soon to receive diminished nutrient loadings including portions of the Laurentian Great Lakes, Shagawa and Detroit Lakes in Minnesota, Lake Sammamish in Washington and the Bay of Quinte in Ontario. As part of an investigation to assess the trophic status of the Muskoka Lakes - a lake system located in the Precambrian Shield region of southern Ontario - a multi-year study was initiated in 1969 to determine whether phosphorus removal effected at sewage treatment plants discharging to the catchment basin of Gravenhurst Bay of Lake Muskoka would alleviate severe growths of "water-bloom" forming blue-green algae. Water quality conditions for the "pre-phosphorus removal era" (1969-1970) were documented by Michalski et al (1973). Preliminary results covering the first two years (1972 and 1973) of the "post-removal" period were presented at the 19th Congress of the International Association of Limnology in Winnipeg, 1974. The purpose of this presentation is to highlight and update information on the limnology of Gravenhurst Bay with a view to clarifying and confirming trends to improved water quality.

DESCRIPTION OF THE STUDY AREA

Gravenhurst Bay is located approximately 130 km north of Lake Ontario and 40 km east of Georgian Bay of Lake Huron (Figure 1). The watershed consists of shallow outwash sands which cover or partially cover igneous metamorphic rock. Gravenhurst Bay, which occupies an area of 4.0 km^2 with a maximum depth of 17m and a volume of 2.8 x $10^7 m^3$ is effectively isolated by a small narrows from downstream Muskoka Lake, a larger (49.5 km^2), deeper (67m), oligotrophic to mesotrophic system (see Michalski et al. 1973). Water from Muskoka Lake drains eastward to Georgian Bay via the Moon and Muskoka Rivers. The calculated annual daily flow to and from Gravenhurst Bay is 4.17 x $10^4 m^3$/day, providing a theoretical turnover time of 1.85 years. Mean monthly temperatures for the study area for 1969 and 1970 ranged between a minimum of -20°C and a maximum of 25.7°C. Total annual precipitation approximates 1m. The Bay is characterized by 33-35 ice-free weeks per year; maximum ice thickness approximates 1m.

Located in the heart of Ontario's summer and winter vacation resort area, Gravenhurst Bay is affected by both a transient and resident population. The shoreline of the Bay is developed for summer recreational activities having approximately 300 cottages and/or permanent residences; all shoreline lots are serviced by conventional septic tank-tile field systems. Prior to August of 1971 domestic wastes from two-thirds of the population of the municipality of Gravenhurst (i.e. 6,283, 1971 census) were treated in a conventional activated sludge treatment plant with a rated hydraulic capacity of 2,043 m^3/day in dry weather flow. The plant was designed to accommodate wastes from 4,000 persons with an organic loading of 293 kg B.O.D./day. Approximately 90% B.O.D. and suspended solids reduction are achieved at this plant. In addition, domestic wastes from the Ontario Hospital and the Ontario Fire College on Gravenhurst Bay are directed to an extended aeration treatment plant with a rated hydraulic capacity of 320 m^3/day having an organic loading capacity of 100 kg B.O.D./day. Samples collected from the sewage treatment plant discharge streams at frequent intervals since May of 1966 indicate that total phosphorus reductions in excess of 90% have occurred following implementation of full-scale phosphorus removal facilities. Total nitrogen concentrations were less affected (i.e. a 55% reduction was attained) through alterations in treatment. As phosphorus

inputs to the Bay from agricultural runoff and industrial discharges are virtually non-existant, the situation afforded an excellent opportunity to evaluate the role of sewage-source phosphorus in its singular capacity "to limit" phytoplankton growth.

METHODS

Field methods

At approximate weekly intervals during the ice-free seasons of the years 1969-1973, visits were made to a single, centrally-located deep-water station (see Figure 1). Water clarity was measured using a Secchi disc (30 cm). Water temperatures were recorded employing a telethermometer (Model FT3 Hydrographic Thermistor) which was calibrated against a standard laboratory thermometer (accuracy 0.5°C); readings were taken at each meter of depth, although fewer readings sufficed when homothermous or near-homothermous conditions existed. Generally, oxygen concentrations were determined using the azide modification of the Winkler method from point-source epilimnial (1.0m) and hypolimnial samples (1.0 or 2.0m above bottom). However, under conditions of thermal stratification, up to 12 depths were sampled; particular attention was directed to establishing the oxygen regime in the vicinity of the metalimnion.

During the initial phase of the study, samples for pH, free CO_2, alkalinity and conductivity were collected from a depth of 1m as well as at 1 or 2m above bottom in 250 ml gas bottles and were held in a portable cooler for transit to the field laboratory. The pH of a 100 ml aliquot was measured using a Portomatic pH meter (Model 175 - Instrumentation Laboratories Inc.) Free CO_2 and total alkalinity were determined titrimetrically to appropriate end point pH values of 8.3 and 4.3 respectively. Conductivity was determined with an Electronic Switch Gear - Model MC-1 Mark V meter. Final recordings (μmhos/cm^3) were temperature adjusted to 25.0°C. During the latter years of this study, all analyses were carried out at the Ministry laboratories in Toronto.

Samples for total phosphorus, nitrogen, silica, iron, inorganic carbon, chlorophyll a and phytoplankton were secured as composites through the euphotic zone (calculated as twice the Secchi disc depth). This was accomplished by lowering and raising a 1000ml bottle fitted with a restricted inlet through the water column at a rate allowing complete filling as the bottle was

retrieved to the surface. Additionally, samples for the above-mentioned nutrients were collected from 1 or 2m above bottom with a Van Dorn bottle. The chlorophyll a samples were treated with 1 ml of a 2% suspension of magnesium carbonate; 300-1,000 ml of this sample were filtered under vacuum pressure in the Mobile Laboratory (or at the main laboratory in Toronto) using a 1.2μ millipore filter, followed by cold storage in plastic containers until shipment to Toronto. All algal samples were preserved with 10 ml of Lugol's iodine solution and forwarded to the Ministry of the Environment's Limnology and Toxicity Section's laboratories (formerly Biology Branch, Ontario Water Resources Commission) in Toronto for analyses.

Laboratory methods

Chemical determinations performed on each water sample included total phosphorus (as μg P/l), total Kjeldahl, nitrate, free ammonia and nitrite nitrogen (as mg N/l), orthosilicate (molybdate reactive portion of soluble silica expressed as mg SiO_2/l), iron (as mg Fe/l) and inorganic carbon (as mg C/l). All chemical analyses including chlorophyll a determinations were carried out according to standard techniques utilized by the Water Quality and Environmental Trace Contaminants Sections of the Ministry. Phytoplankton identification and enumeration methodologies are outlined in Michalski et al. (1973).

RESULTS AND DISCUSSION

Temperature and Light Characteristics

Well-defined thermoclines comparable to second order lakes of Hutchinson (1957) characterized Gravenhurst Bay during the six year study period. The times of formation and positions of the metalimnia for 1969, 1973 and 1974 are presented in Figure 2. Of interest is that the euphotic zone was situated above the metalimnion throughout most of 1969 and 1974; in contrast, extension of this zone through the metalimnion into the upper hypolimnion was evident during the summer months of 1973. The position of the lower limit of the euphotic zone appears to determine metalimnetic dissolved oxygen concentrations (discussed below). There was a downward movement of the metalimnion in the late summer and fall each year. A trend to improved water clarity has materialized since the implementation of phosphorus removal facilities in 1971 (Table 1 and Figure 3). For example, individual mid-summer readings

Table 1: Extreme and mean Secchi disc values and euphotic zone chlorophyll *a* concentrations at a centrally-located station in Gravenhurst Bay, 1969-1974.

	Secchi disc (m)			Chlorophyll *a* (μg/l)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
1969	0.8	4.9	2.6	2.0	33.0	12.8
1970	1.7	5.0	3.0	0.8	14.4	6.0
1971	0.8	3.0	1.9	1.5	82.0	13.8
1972	1.5	4.5	3.1	1.0	25.0	8.0
1973	1.7	4.8	3.2	0.7	29.0	7.2
1974	1.4	4.2	2.7	0.2	25.0	5.0

following phosphorus removal were generally higher than during the pre-phosphorus removal years.

There has been considerable within year and between year variations in water clarity; however, the minimum Secchi disc readings have improved. Values less than one meter were observed before phosphorus removal started, in 1971 but 1.4 meters was the lowest recording since 1971 (Table 1, Figure 4).

The average of all results prior to reduced phosphorus loadings was 2.5m, while the average for 1972, 1973 and 1974 was 3.0m.

Water Chemistry Characteristics

Higher pH prevailed in the surface waters relative to levels in the strata of water 1m above bottom (Table 2). In contrast, deep water alkalinity, and free CO_2 exceeded values characterizing the upper waters of the Bay. Generally, free CO_2 was barely detectable in the surface layers, especially during mid-summer period. Only minor year-to-year variations were evident over the six years of study. The somewhat lower maximum pH values and higher minimum free CO_2 concentrations found since 1971 (Table 2) likely resulted from decreased carbon assimilation by smaller standing stocks of phytoplankton.

Dissolved Oxygen

Gravenhurst Bay was characterized by a negative heterograde dissolved oxygen distribution during the three pre-phosphorus removal years. This metalimnetic sag was particularly evident in August of 1969 with concentrations less than 1 mg/l at 6m of depth (Figure 5). Data collected in 1972 and 1973 did not indicate a mid-thermocline dissolved oxygen depletion, probably owing to the deepened compensation depth. Observations during 1974 indicate a return to low metalimnetic concentrations (Figure 5) corresponding to the poorer light transmissions, especially during the late summer and early fall.

Bottom water dissolved oxygen depletion rates have not changed appreciably over the six years; rates were 0.10 mg/l/day at 13m in 1969, 0.16 mg/l/day at 14m in 1973 and 0.14 mg/l/day at 14m in 1974.

Nutrient Characteristics

Inorganic carbon concentrations in the euphotic zone ranged from 1.6 mg/l to 5.9 mg/l during the ice-free period of 1969 with little variation over the five subsequent years of measurement; these concentrations are typical of values recorded from other soft-water Precambrian lakes (Johnson and Michalski 1970; Armstrong and Schindler 1971; Schindler and Nighswander 1970). Although free carbon dioxide was frequently undectectable during mid-summer in the surface

Table 2: Extreme and mean pH, alkalinity (as mg/l $CaCO_3$), conductivity (as µmhos/cm^3 at 25°C) and Free CO_2 (as mg/l CO_2) at 1m (or as a composite through the euphotic zone) and 14m of depth at a centrally-located station in Gravenhurst Bay.

	Depth	1969-1970			1971			1972			1973			1974		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
pH	1m	6.2	8.6	6.9	6.0	9.0	7.0	6.1	8.5	6.8	6.4	8.6	7.3	6.3	8.0	7.0
	14m	5.5	7.1	6.2	5.3	7.5	6.2	5.8	7.5	6.3	6.3	8.5	7.0	6.1	8.3	6.8
Alk.	1m	6.8	12.0	9.6	6.5	12.0	9.4	7.7	12.3	9.4	8.0	12.0	10.0	9	19	12
	14m	7.1	12.6	9.8	6.4	17.4	10.3	6.6	15.3	9.5	9.0	18.0	13.7	8	23	14
Cond.	1m	44.0	88.3	50.0	52.1	60.0	56.3	50.0	75.0	58.9	57.0	78.0	61.6	59	78	66
	14m	44.3	99.1	63.2	54.0	65.0	61.4	51.0	68.0	63.6	60.0	78.0	69.0	59	75	71
Free CO_2	1m	0	9.0	2.9	0	6.1	2.0	0	5.0	2.4	1.3	3.4	2.3	0.9	7.0	2.7
	14m	2.0	38.6	13.5	2.4	21.9	11.9	0.8	18.6	9.1	3.1	17.0	8.7	2.0	20	11.5

waters, it is felt that the inorganic carbon reserve as bicarbonate as well as atmospheric invasion (Emerson et al. 1973) were sufficient to allow photosynthesis to be controlled or limited by other nutritional factors.

Total P concentrations in the euphotic zone of Gravenhurst Bay were far in excess of values normally associated with Shield lakes unaffected by municipal sewage inputs (Ontario Ministry of the Environment, unpublished data; Armstrong and Schindler 1971. The decreased phosphorus loadings to Gravenhurst Bay were well reflected in the euphotic zone where mean total P concentrations during the ice-free periods were 39, 40 and 51 μg P/l during 1969, 1970 and 1971, respectively and decreased to 36, 32 and 25 μg P/l by 1972, 1973 and 1974, respectively (Figure 4). Two very high euphotic zone concentrations of 100 and 140 μg P/l on July 25 and August 2, 1973 might be explained by very heavy rainfall (6 cm) during the last week of July. Minimum mid-summer euphotic zone phosphorus concentrations for 1969, 1970 and 1971, (the pre-phosphorus removal era) were 31, 22 and 20 μg/l, respectively; levels for similar periods of 1972, 1973 and 1974 were 14, 19 and 10 μg/l, respectively (Figure 4). Throughout the ice-free period, bottom water concentrations were consistently higher than in the euphotic zone (Figure 6), especially in late summer when concentrations in excess of 200 μg P/l were frequently found. Although the 1972 data (the first year after initial reduction in P loading) demonstrated reduced bottom-water concentrations in relation to the 1969, 1970 and 1971 information, reasons for a return to the very high bottom water concentrations in 1973 and 1974 (Figure 6) are not clear at this time.

The trend to higher inorganic nitrogen concentrations (NH_3-N + NO_3^- -N + NO_2^--N) during the ice-free periods is very clearly defined (Figures 4 and 7), with mugh higher euphotic zone inorganic nitrogen concentrations present after the initiation of the phosphorus removal programme in 1971. For example, during 1969, 1970, 1971 inorganic N was frequently present in the euphotic zone in amounts below the analytical limits of detection (10 μg NH_3-N and NO_3-N/l) and averaged 64, 64 and 84 μg N/l, respectively during the ice-free periods. On the other hand, euphotic zone concentrations during similar periods for 1972, 1973 and 1974 were substantially higher at 135, 147 and 185 μg N/l, respectively. The declining total P and to some extent, slightly rising total N concentrations have resulted in considerable higher N:P ratios in the euphotic zone of 15.4, 18.8 and 25.6 during 1972, 1973 and 1974 respectively; in contrast, N:P ratios during 1969, 1970 and 1971 were 11.4, 10.5 and 12.4 respectively (Figures 4 and 8).

The low euphotic zone silica levels (generally less than 2 mg SiO_2/l) are typical of Shield lakes. Bottom-water concentrations have been characteristically higher over the five years of study with mid-to late summer values ranging between 3 and 4 mg SiO_2/l. The seasonal distribution of silica is of interest in light of early summer growths of diatoms in the Bay. From 1969 through 1972, depletion of SiO_2 to concentrations ranging between 0.05 and 0.2 mg/l have occurred in mid-June. In 1973 however, such depletions did not occur until near the end of July.

Chlorophyll *a* and Phytoplankton Stocks

Experiences have indicated that spring and/or fall maxima normally characterize most of Ontario's Precambrian Shield lakes; as well, ice-free mean values in unaffected lakes rarely exceed 2-4 µg/l. As indicated in Figure 9 and Table 1, consistent seasonal patterns of chlorophyll *a* were not apparent over the five years of study; concentrations frequently exceeded 15 µg/l (as high as 82 µg/l on July 15, 1971) during the mid-summer periods of 1969 through 1971 and reduced recreational activities such as swimming, boating and water skiing, impaired water treatment supply operations and diminished the aesthetic quality of the Bay. Excessive algal growths have not developed during the summer months of the post-phosphorus removal period and water-oriented recreational pursuits have not diminished. The minimum chlorophyll *a* concentrations have decreased since 1971 (Table 1).

The 1970 and 1971 species composition and seasonal development of phytoplankton closely resembled those of 1969; consequently, only the 1969 data have been presented (Figure 10) as typical of the pre-phosphorus removal conditions. As in the case of chlorophyll *a*, definite patterns in seasonal development were not detected in the years 1969-1971, as excessive algal densities were frequently encountered during the mid-summer months. Michalski et *al*. (1973) described the enriched nature of the Bay by comparing the breakdown in the normal bimodal pattern of development to similar conditions reported by Davis (1964) for eutrophic Lake Erie. As indicated in Figure 10, phytoplankton biomass was more uniformly distributed during the ice-free periods in the two years following reduced phosphorus loadings to the Bay. The mean 1972-1973 areal standard unit value of 1,406 was 50% less than the 1960-1970-1971 mean of 2,717, reflecting the effects of decreased phosphorus concentrations.

A number of shifts in species dominancy, although not influential in terms of overall composition of the flora, are worth mentioning. Our "before phosphosur removal data" clearly indicate that ecological requirements were not

suitable for chrysophytes. As pointed out by Michalski et al. (1973), Schindler and Nighswander (1970), and Schindler and Holmgren (1971), chrysophycean species normally constitute a high proportion of the total biomass in nutrient deficient lakes of the Precambrian Shield. Early indications of "oligotrophication" in the Bay are suggested by the appearance of modest densities of Synura uvella Ehr., Dinobryon spp. and a number of other unidentified chrysomonads. In 1969-1971, the waters of the Bay were characterized by relatively high numbers of a single dinophyte. Ceratium hirundinella (O. Mull) Dujardin; this species, which is ubiquitous but generally prefers enriched conditions, is gradually diminishing from the Bay (Figure 10). Although Aphanizomenon flos-aquae (L.) Ralfs and Anabaena spp. (Mainly A. flos-aquae) remain the dominating blue-green forms. There has been a seven-fold decrease since 1971; with combined mean a.s.u. values of 702 for 1969-1971 and only 104 for 1972-1973. A number of species of chroococcalean blue-green algae (Gomphosphaeria lacustris Chodat, Chroococcus spp.) - which were not noted prior to 1972 and which are common to the flora of unenriched lakes of the Shield (Michalski and Robinson 1969, Michalski 1971, Michalski et al. 1973, Schindler and Nighswander 1970 and Schindler and Holmgren 1971) - have been identified and enumerated in the 1972 and 1973 samples, again suggesting a trend towards oligotrophy. Although 1974 phytoplankton data are not yet available, the above mentioned trends to "oligotrophication" of the Bay are substantiated by the 1974 chlorophyll a analyses which indicate a trend to a biomodal seasonal pattern of development more typical of unenriched lakes (Figure 9). The major species currently existing in the Bay, Cryptomonas spp. Ehr., Rhodomonas minuta Skuja, Asterionella formosa Hass, Fragilaria crotonensis Kitt. and Anabaena spp. dominated during the pre-phosphorus removal period so a degree of caution is therefore expressed relative to formulating conclusions regarding the permanence of improvements on the basis of alterations in species composition.

Nutrient-phytoplankton Relationships

Results of water quality evaluations in Ontario's recreational lakes over the past several years have enabled staff of the Ministry of the Environment to develop a near-hyperbolic relationship between Secchi disc visibility and chlorophyll a concentrations (Figure 11). This relationship has been based on data collected from approximately 190 lakes in the Province. Of some interest is that for low chlorophyll a levels (i.e. 0.5 - 1.0 μg/l), a wide

range in Secchi disc values occurs, whereas for high chlorophyll a concentrations the range in transparency is much narrower. Consequently, a considerable decrease in algal densities in eutrophic waters would be necessary before an improvement in water clarity would become publicly noticeable. Edmondson (1972) suggested that "this relationship might well give rise to a subjective public impression of a threshold effect or 'trigger' effect" and as such should have a particular impact as a simple educational or interpretive tool. For example, in 1971 Little Otter Lake was characterized by mean Secchi disc values and chlorophyll a concentrations of 1.0m and 31 μg/l, respectively. Following eliminations of a significant proportion of the total artificial phosphorus loading to the lake, spectacular water quality improvements materialized (Michalski and Conroy 1973). These changes are clearly apparent in Figure 10 as Little Otter Lake moved along the curve from a highly enriched position (No. 11) to a decidedly improved position (No. 12). With specific reference to Gravenhurst Bay, the general trend to improved water quality over the six year period can be readily seen (Figure 11) and appreciated by persons with little exposure to scientific training.

The improvements since 1971 in Gravenhurst Bay relating to a reduction in the density of suspended algae and corresponding increase in water transparency are most important from a water use potential and an aesthetic point of view. Similarly, Edmondson (1972) and Ahlgren (1972) have demonstrated lower chlorophyll a and higher Secchi disc transparencies in Lakes Washington and Norrviken, respectively in the years immediately following sewage diversion from the lake. Both of the above authors reported a change in the composition of the phytoplankton but Cyanophyceae remained the dominant class in both lakes. Similarly the cyanophytes A. flos-aquae and Anabaena spp. – well-known indicators of nutrient enrichment – have remained to dominate the flora of Gravenhurst Bay. The shift towards increasing numbers of Chrysophyceae which are more typical of unenriched Shield lakes represents a significant improvement in water quality from a users point of view as representatives of Chrysophyceae are much less noticeable and offensive than cyanophytes, even when present in similar densities, owing to the obnoxious "bloom-forming" tendencies of cyanophytes.

Mean phytoplankton biomass as areal standard units is significantly correlated ($r = 0.917$) with mean chlorophyll a during ice-free periods of 1969 through 1973 ($n = 5$); however, mean biomass in terms of areal standard units is better correlated statistically with mean Secchi disc ($r = -.992$) and mean euphotic zone total P ($r = 0.876$) than is chlorophyll a ($r = -.833$ and

r = 0.528, respectively). No such relationships could be established with N or SiO_2 on Secchi disc, chlorophyll a or phytoplankton areal standard units. Although it would appear from these data that P has indeed been an important factor controlling phytoplankton biomass (additionally see Michalski and Conroy 1973, Schindler et al. 1973, Sakamoto 1971, Dillon and Rigler 1974, Schindler and Nighswander 1970 and Michalski et al. 1973), there is evidence to suggest that both N and SiO_2 have at times limited phytoplankton growth. Instances of N limitation to summer phytoplankton growths (Ambuhl 1960, Ryther and Dunstan 1971 and Nicholls 1975) are apparently not common, yet would appear to be peculiar to highly enriched environments. Vollenweider (1973) has suggested that "......though P is the initiating factor, the N metabolism becomes accelerated with increasing eutrophication and this acceleration may likely be driven beyond the point of a simple N-P relationship, probably due to increasing denitrification.... and.... above a certain point, N becomes the controlling factor." Furthermore, evidence exists (Schelske and Stoermer 1972, Lund 1969 and Nicholls 1975) to indicate that silica may limit diatom growth if an abundant supply of P (as results from accelerated cultural eutrophication) enables SiO_2 to be completely exhausted by diatom growth. It would appear therefore, that nutrients other than P, such as N and SiO_2, may become limiting factors in artificially enriched lakes. In point of fact, during the early years of the Gravenhurst Bay study, there have been indications that low concentrations of inorganic N and SiO_2 may have been limiting. However, more recent data suggest that N and SiO_2 limitation has not likely occurred since the effects of reduced P loadings to the Bay have been realized. Additional evidence suggesting a shift from periods of N limitation to P limitation lies in the euphotic zone N:P ratios which have risen dramatically from a mean of 10.5 in 1970 to 25.6 in 1974 during the ice-free periods. Since the Bay most likely has not yet reached a steady state following reduced P loadings in 1971, the response to any further reduction in P loading in terms of shifts in the dominance of major algal groups and individual species as well as trends towards lower standing crops of suspended algae and improved water clarity will in all probability continue to be realized.

Phosphorus Removal and Water Management Implications

Personnel involved in water management programmes in Ontario are placing emphasis on eliminating point-source discharges of phosphorus from conventional sewage treatment plants to reverse conditions of accelerated enrichment in lakes. By 1975, the Government of Ontario expects to have controls in

operations at more than 200 municipal waste-water treatment plants across the Province serving some 4.7 million persons. Recently, Vollenweider (1968) proposed a relatively simple measure of eutrophication using an empirical phosphorus loading - mean depth relationship. The model was employed as a guide in defining the degree of eutrophy in a lake in establishing "Permissible" and "Dangerous" phosphorus loading levels (see Schindler and Nighswander 1970, Schindler et al. 1971, Patalas 1972, Patalas and Salki 1973 and Ahl 1972). Indeed, the relationship was used to provide the rationale leading to government policies to remove phosphorus from sewage discharging to the Great Lakes Basin (Anon, 1969). More recently, Vollenweider (1973) modified his simple loading/mean depth relationship to include the mean residence time of water (τ_W). This latter model is reproduced in Figure 12.

Total phosphorus loadings to Gravenhurst Bay from land drainage, cottages, rainfall and sewage treatment plant discharges were measured and/or calculated and are presented in Table 3. Our input from land drainage (0.009 g P/m^2/year) is less than that reported by Patalas (1972) for Lake Superior (0.015 g P/m^2/year) and Michalski and Conroy (1972) for Little Otter Lake near Parry Sound, Ontario (0.019 g P/m^2/year) but is close to Dillon and Kirchner's (1975) mean export value of 0.010 g P/m^2/year from nearby igenous forested and pastured watersheds.

Annual capita inputs of phosphorus and nitrogen were taken from previous studies (Johnson and Owen 1971) with consideration to the degree of industrialization and type of waste treatment provided by Muskoka municipalities. A phosphorus input of 1.5 kg/capita/year was chosen. Per capita contributions from municipal inputs were used to compute contributions according to Michalski and Robinson (1971). Annual inputs of phosphorus via rainfall was taken as 17 kg/km^2, after Johnson and Owen (1971).

Loadings to Gravenhurst Bay as well as to a number of other lakes are presented in Figure 12. As indicated, the 1969/1970 loading (2.37 g P/m^2/year) for Gravenhurst Bay exceeds the acknowledged "Dangerous Level" (i.e. the upper diagonal). However, once phosphorus removal was effected at the local sewage treatment plants, the "improved" 1972/1974 loading rate (0.40 g P/m^2/year) was such that the relative status for the Bay was reduced from a decidedly eutrophic to a mesotrophic condition. Significantly, the observed limnological changes from a highly enriched lake (i.e. Gravenhurst Bay 1969-1971) to a moderately enriched system (i.e. Gravenhurst Bay 1972-1974) corresponded completely with changes which would be expected on the basis of the chlorophyll a - Secchi disc and Vollenweider (1973) models (see Figures 11 and 12, respectively).

Table 3: Phosphorus loading rates (kg/yr and g P/m^2/year) from land drainage, cottages, rainfall and sewage treatment plant discharges to Gravenhurst Bay 1969 and 1972.

	1969-1971		1972-1974	
	kg/yr	%	kg/yr	%
Land drainage	340	3.5	340	20.7
Cottages	338	3.5	338	20.6
Municipal Input	8,933	92.3	894	54.4
Rainfall	69	0.7	69	4.2
Total	9,680	100.0	1,641	100.0
Loading rate (g P/m^2/year)	2.37		0.40	

A summary of relevant "pre and post-phosphorus removal" data is presented in Table 4, and reveals that major improvements as measured by a variety of trophic indicators have materialized in the Bay following the implementation of a control programme to limit phosphorus inputs.

The Gravenhurst Bay case is the first instance in Ontario where field studies have confirmed, in the short term, the validity of earlier predictions (Michalski et al. 1973). Viewed in this light, one must consider the Province's phosphorus removal programme with a certain amount of optimism.

Table 4: Mean values for relevant "trophic indicator parameters" for Gravenhurst Bay during the pre and post-phosphorus removal years 1969 through 1971 and 1972 through 1974, respectively. Data for total phosphorus, inorganic nitrogen, N:P chlorophyll _a_ and phytoplankton stocks are based on samples collected through the euphotic zone.

	Pre-phosphorus removal conditions 1969/1970/1971	Post-phosphorus removal conditions 1972/1973/1974
Total Phosphorus Loadings (g P/m^2/year)	2.37	0.40
Secchi disc (m)	2.5	3.0
Total Phosphorus (μg P/l)	43	30
Inorganic Nitrogen (μg N/l)	71	156
N:P	11.4	19.9
Chlorophyll _a_ (μg/l)	10.8	6.7
Phytoplankton*		
a) Quantity (a.s.u./ml)	2,717	1,424
b) Dominant Species	_Asterionella formosa_ _Aphanizomenon flos-aquae_ _Anabaena_ spp. _Ceratium hirundinella_	_Asterionella formosa_ _Aphanizomenon flos-aquae_ _Anabaena_ spp. _Cryptomonas_ spp. _Rhodomonas minuta_ _Fragilaria crotonensis_

* Post-phosphorus removal period 1972 and 1973 only, since 1974 phytoplankton data are not yet available. Although not dominant, species of _Synura_, _Dinobryon_, _Chroococcus_ and _Gomphosphaeria lacustris_ were more prevalent in the plankton during the post-P removal years.

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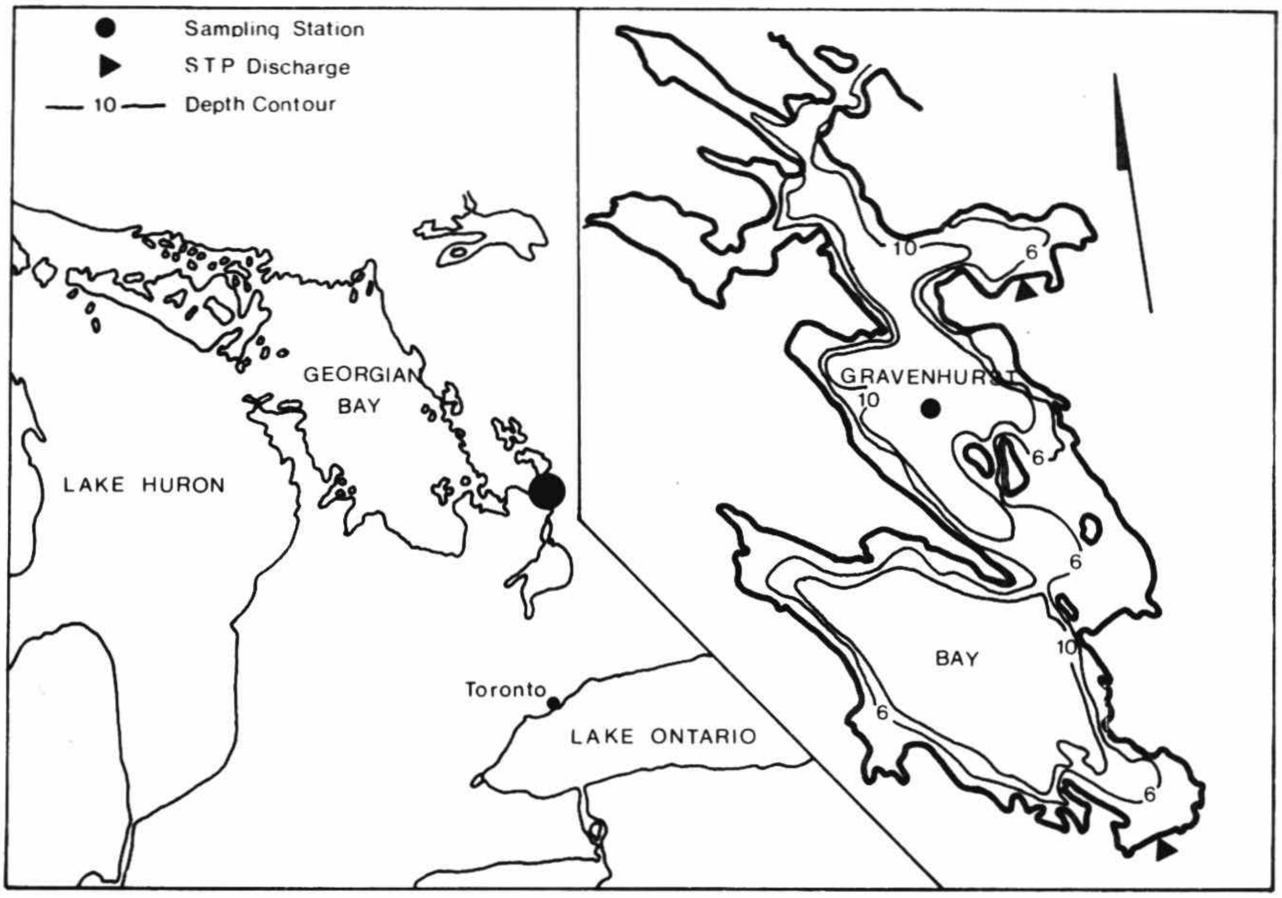

Figure 1: Diagrammatic representation of the study area. Main-lake sampling station as well as sewage treatment plant discharge points are illustrated.

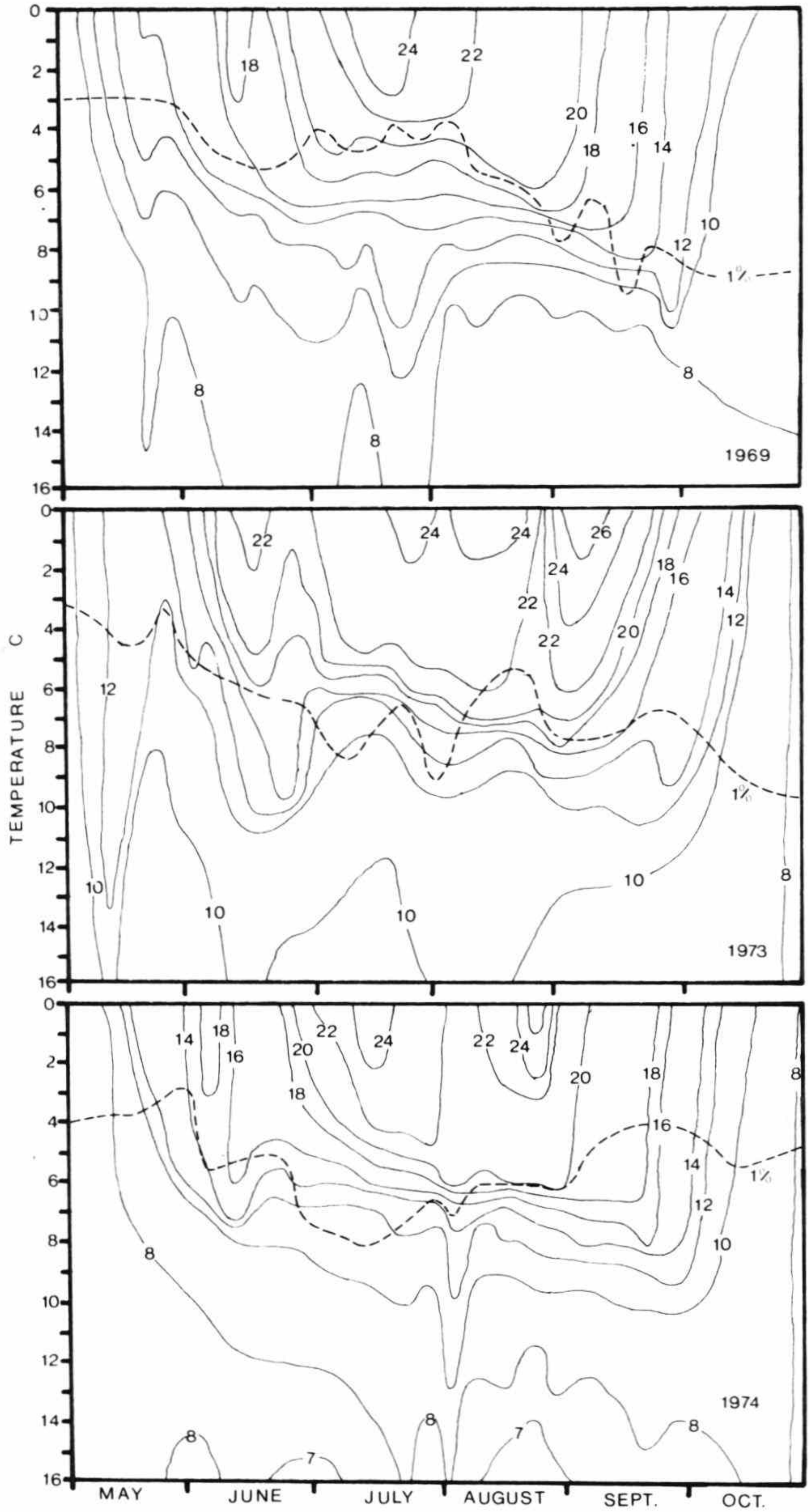

Figure 2: Isotherms (^{o}C) at a centrally-located station in Gravenhurst Bay based on weekly measurements May-October, 1969 1973 and 1974.

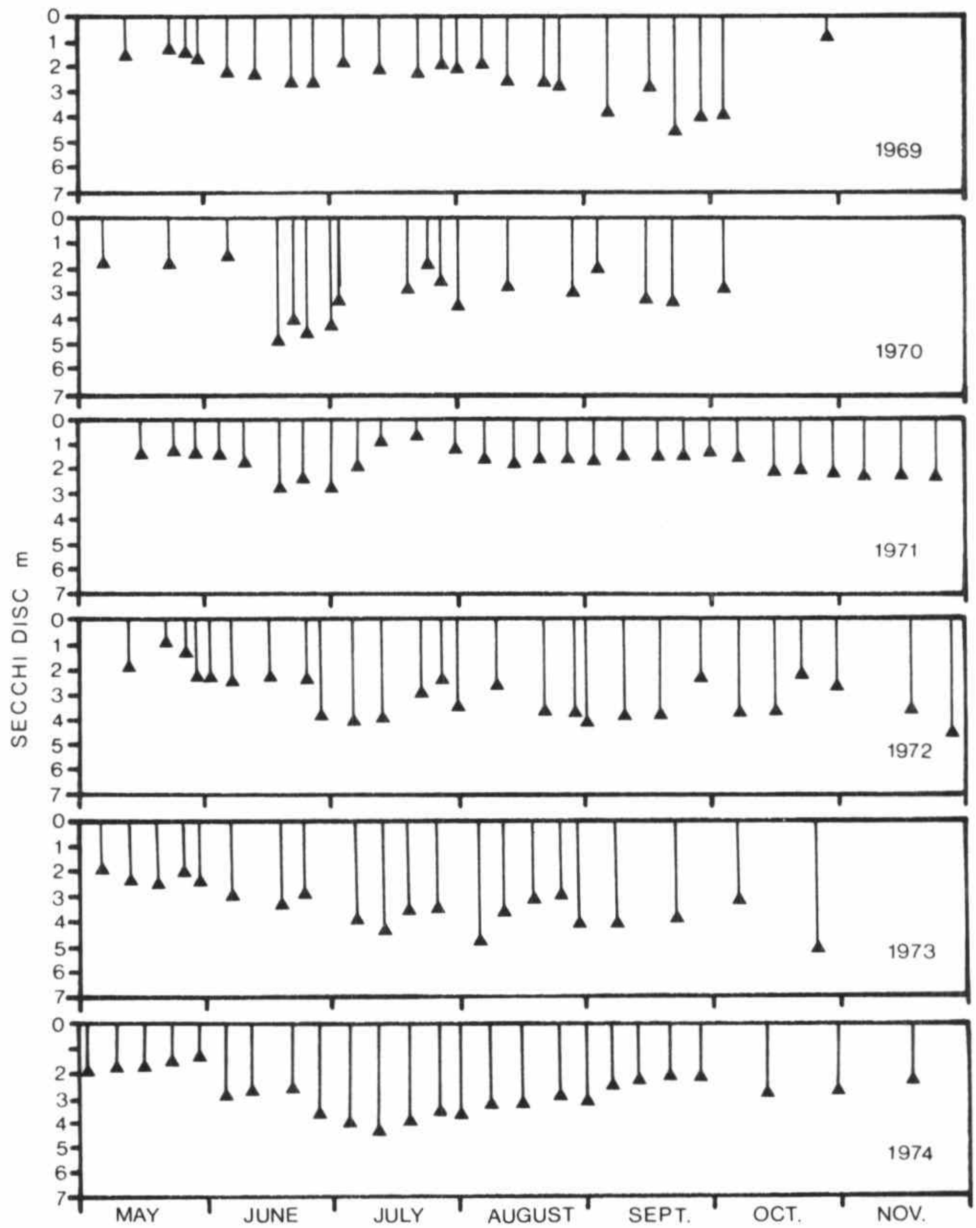

Figure 3: Seasonal variations in Secchi disc visibility (m) at a centrally-located station in Gravenhurst Bay during the ice-free periods, 1969-1974.

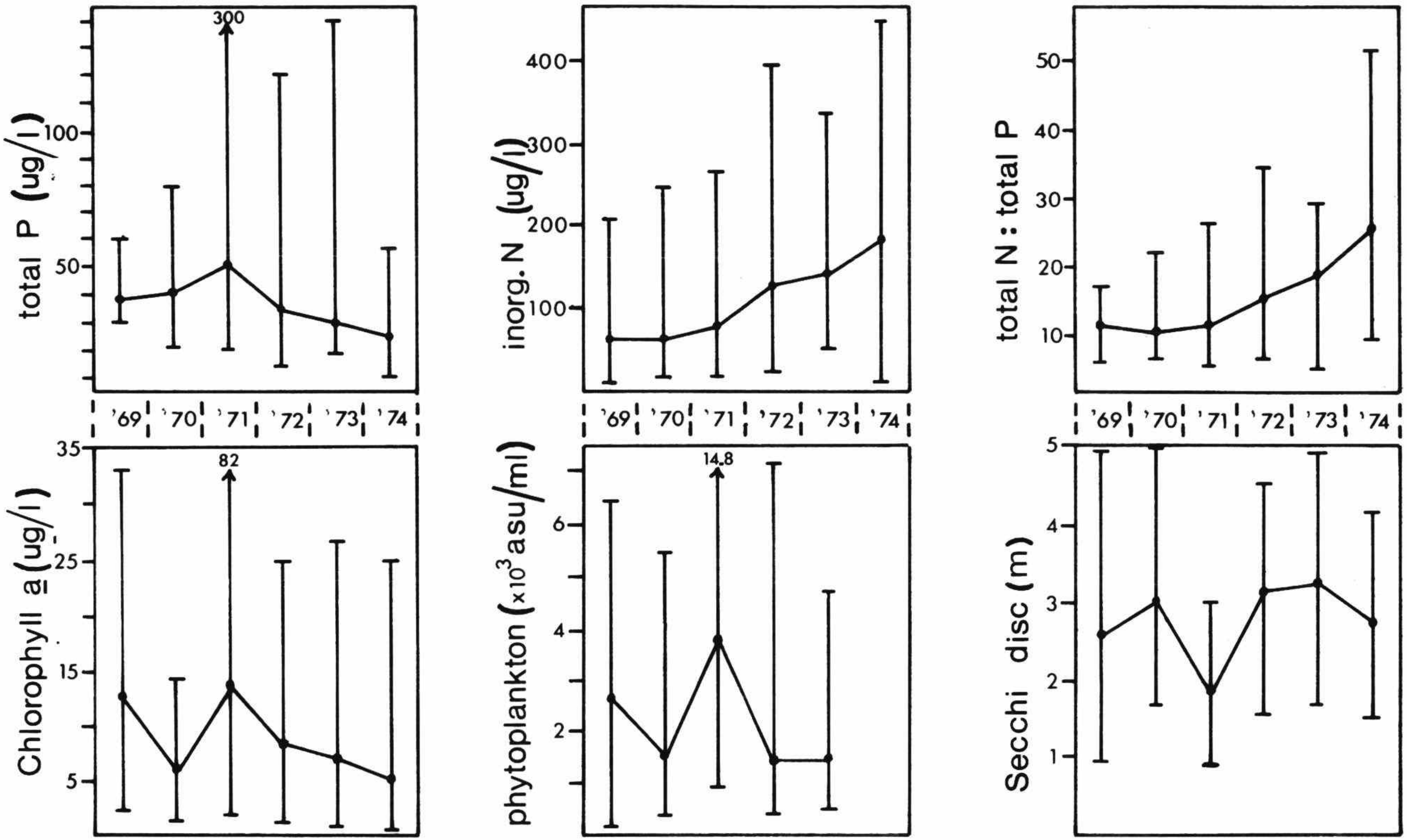

Figure 4: Annual ice-free period mean, minimum and maximum values for euphotic zone concentrations of total phosphorus, inorganic nitrogen (NH_3-N+NO_3^--N+NO_2^--N), total nitrogen-to-phosphorus ratios, chlorophyll a, phytoplankton biomass and Secchi disc visibilities in Gravenhurst Bay from 1969 through 1974. Phytoplankton data from 1974 are not yet available.

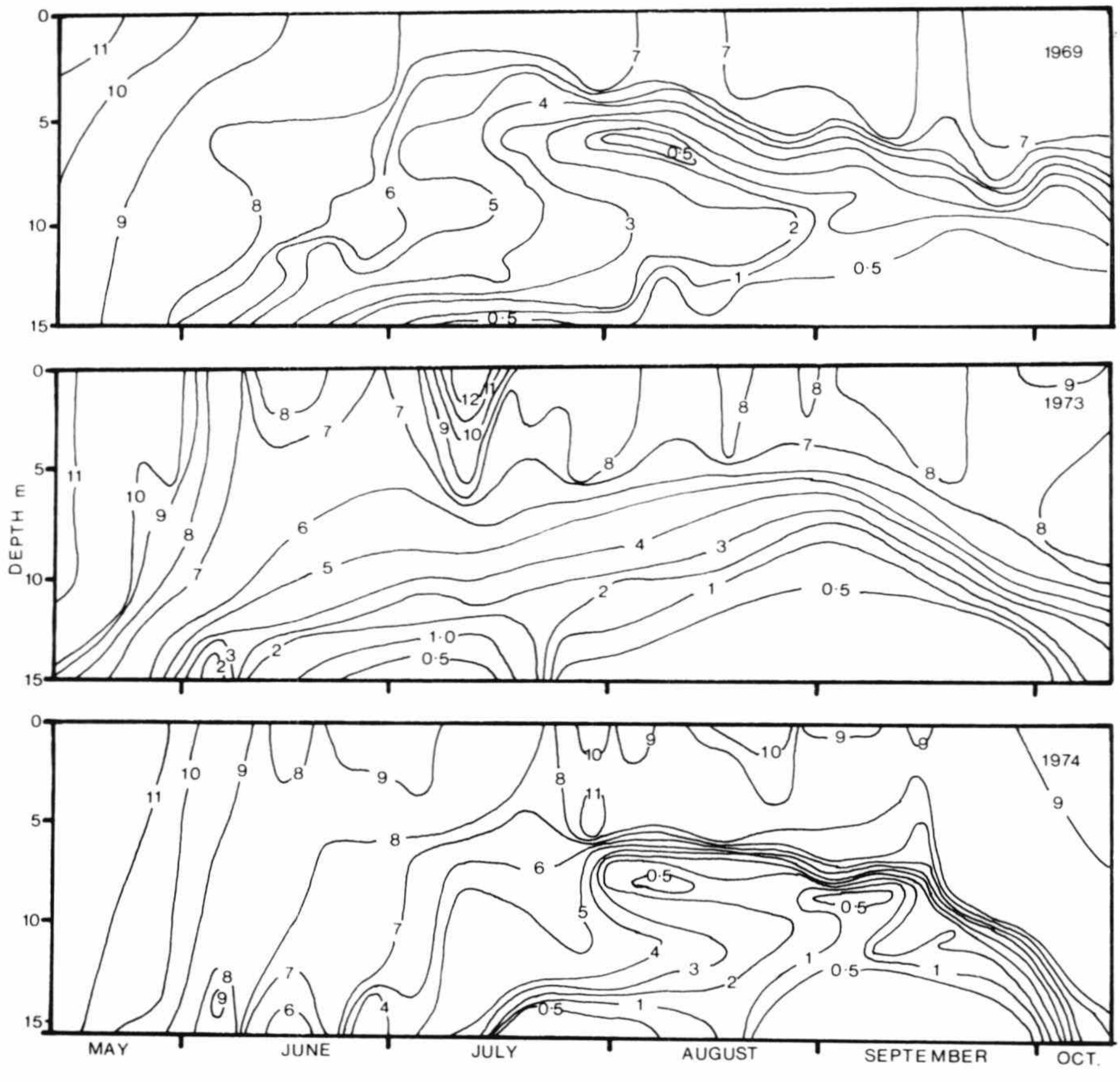

Figure 5: Seasonal isopleths of dissolved oxygen (mg/l) in Gravenhurst Bay based on weekly measurements, May-October 1969, 1973 and 1974.

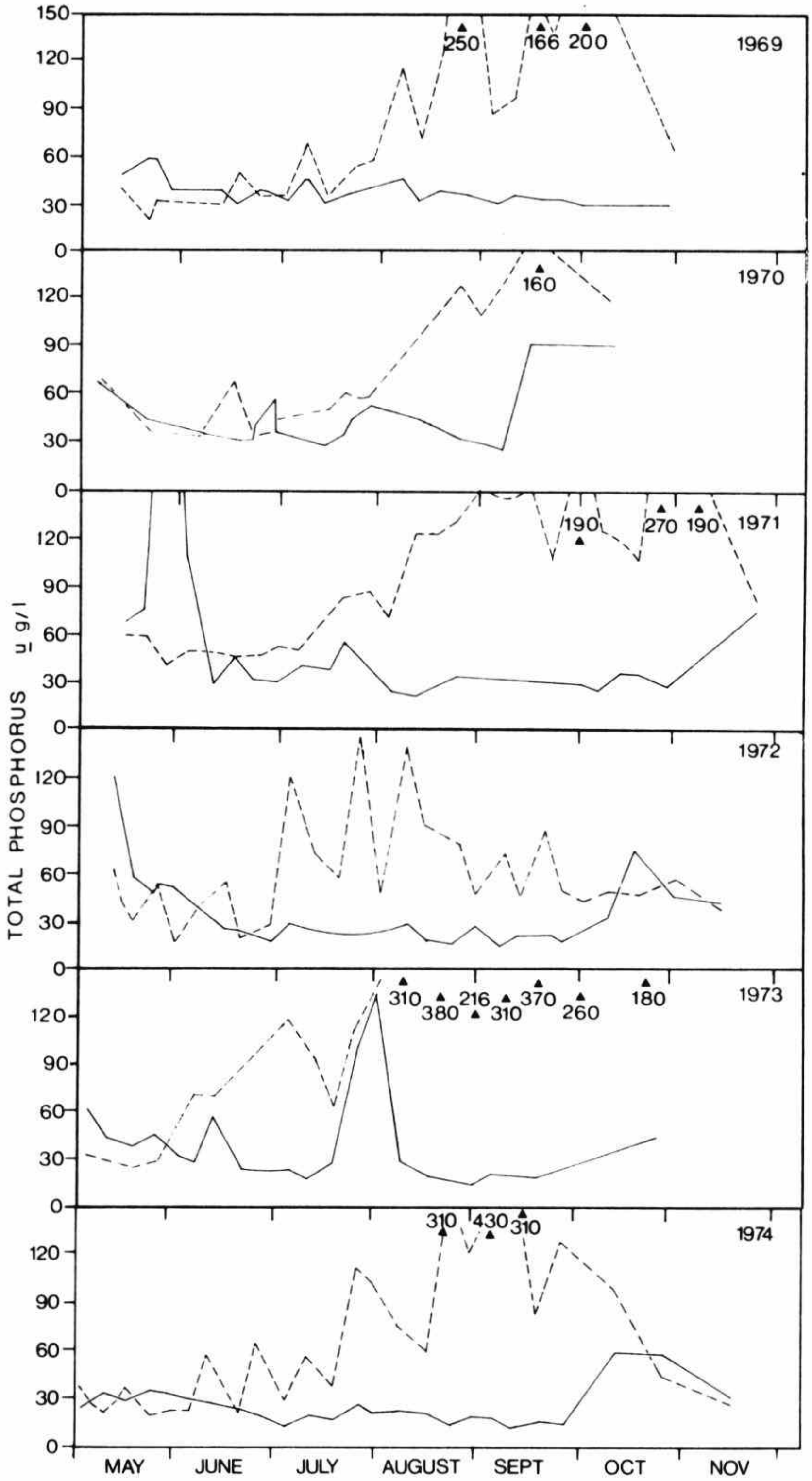

Figure 6: Seasonal distributions of total phosphorus (µg P/l) in the euphotic zone (solid lines) and at 1m or 2m above bottom (broken lines) at a centrally-located station in Gravenhurst Bay during ice free periods, 1969-1974.

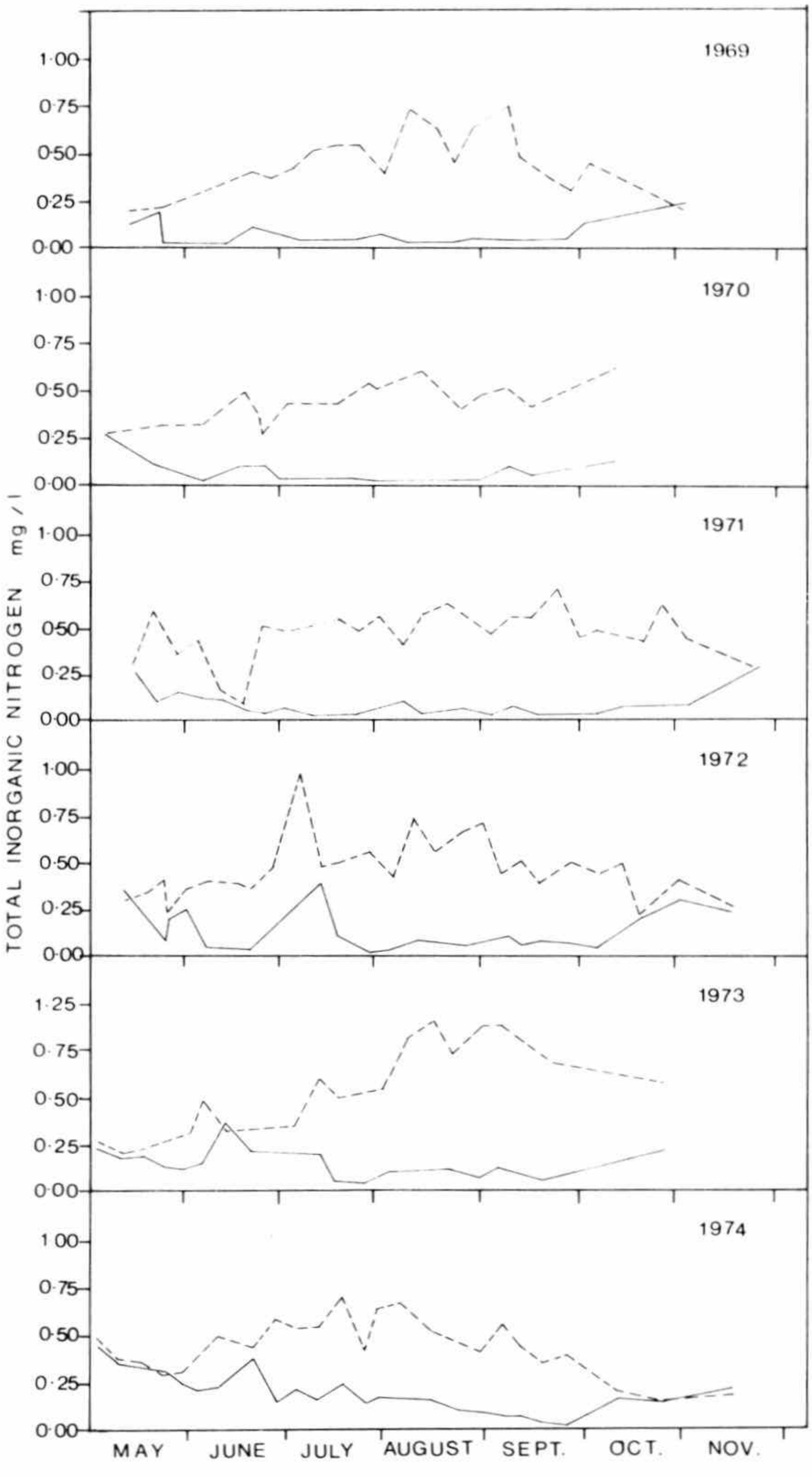

Figure 7: Seasonal distributions of total inorganic nitrogen (expressed as mg/l free amonia, nitrate and nitrite nitrogen) in the euphotic zone (solid lines) and at 1m or 2m above bottom (broken lines) at a centrally-located station in Gravenhurst Bay during ice-free periods, 1969-1974.

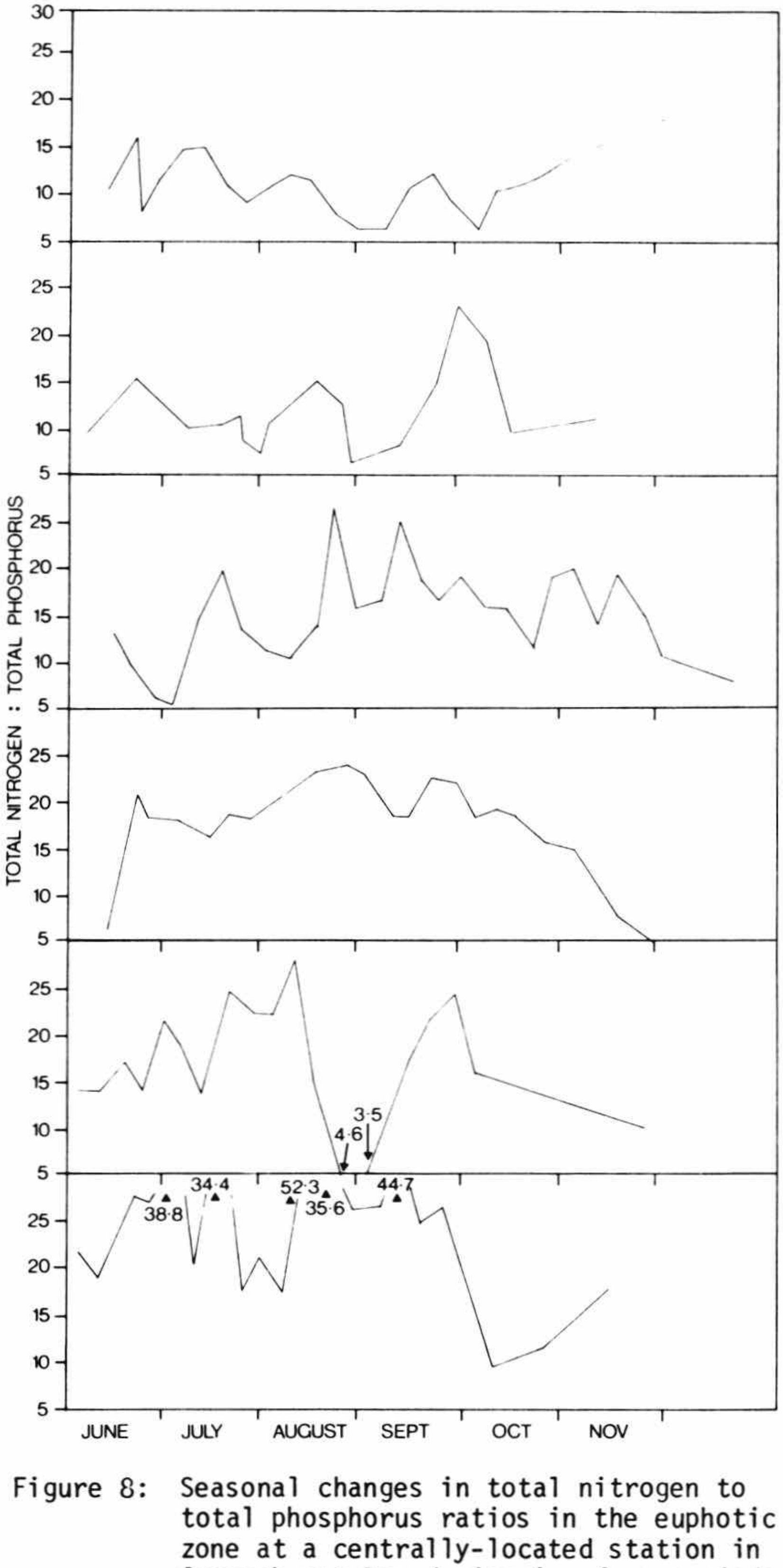

Figure 8: Seasonal changes in total nitrogen to total phosphorus ratios in the euphotic zone at a centrally-located station in Gravenhurst Bay during ice-free periods, 1969-1974.

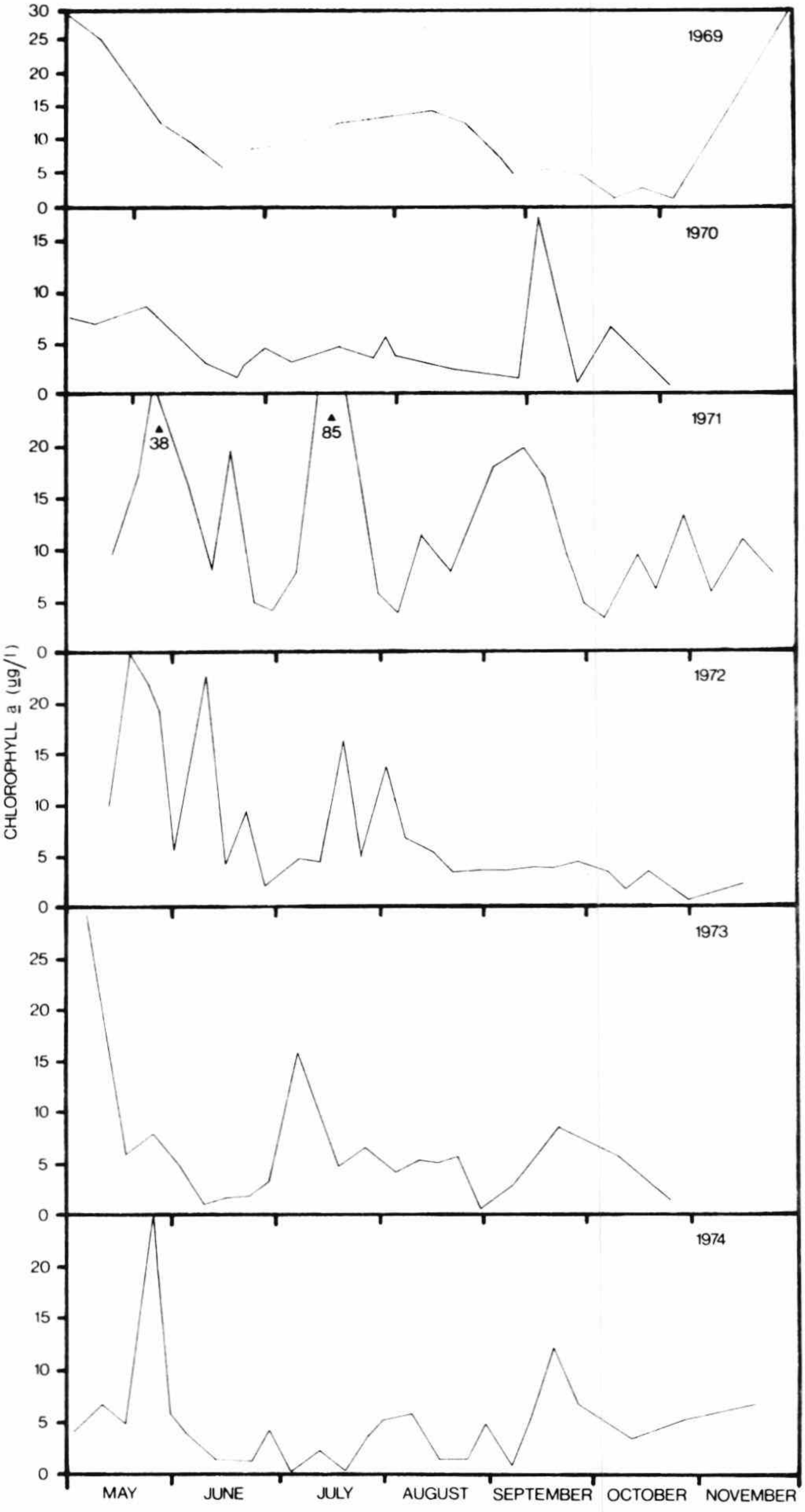

Figure 9: Seasonal distribution of chlorophyll a (µg/l) in the euphotic zone at a centrally-located station in Gravenhurst Bay during ice-free periods, 1969-1974.

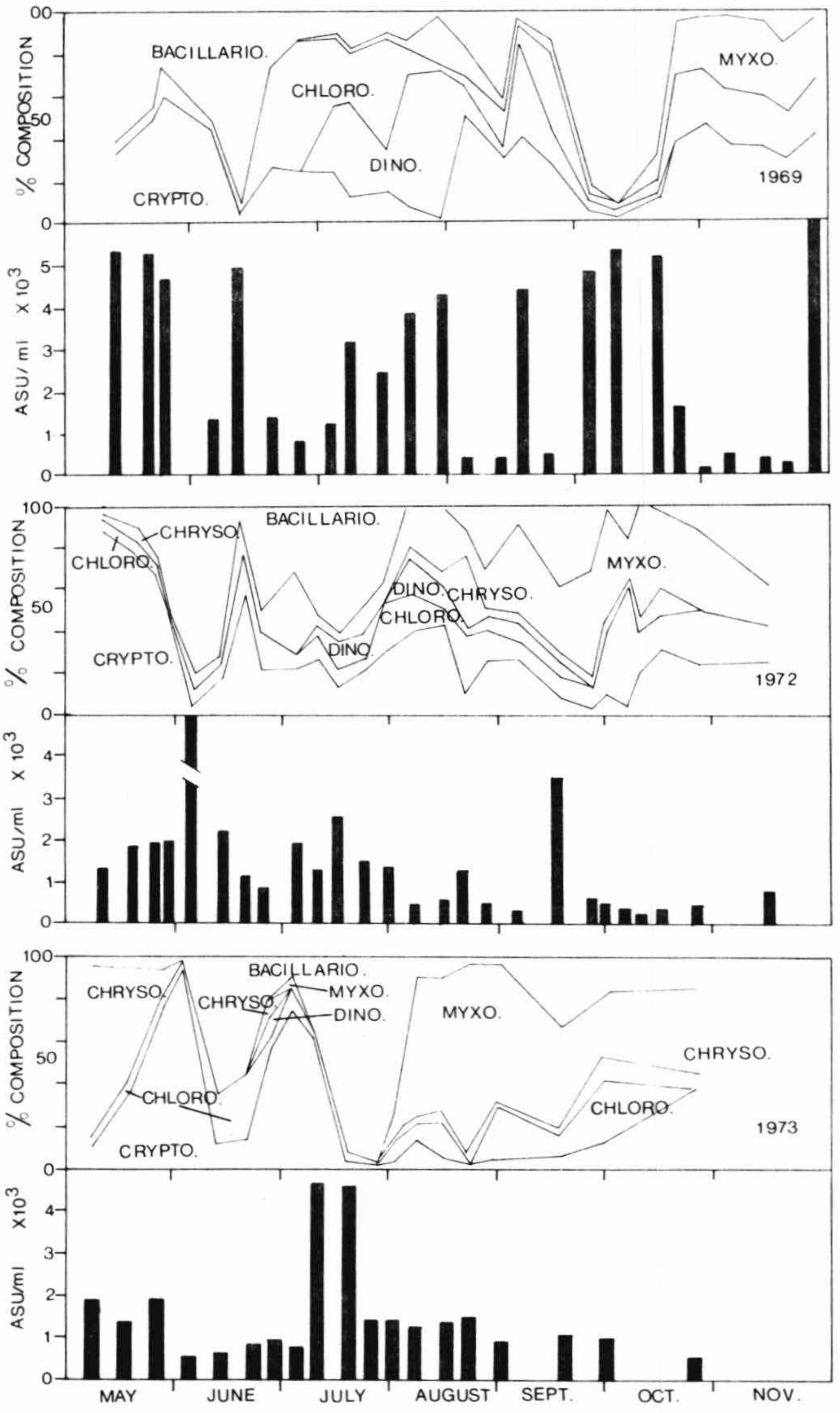

Figure 10: Seasonal distribution of phytoplankton stocks and composition in the euphotic zone at a centrally-located station in Gravenhurst Bay during ice-free periods, 1969, 1972 and 1973. Quantitative results are expressed as Areal Standard Units (A.S.U.)/ml.

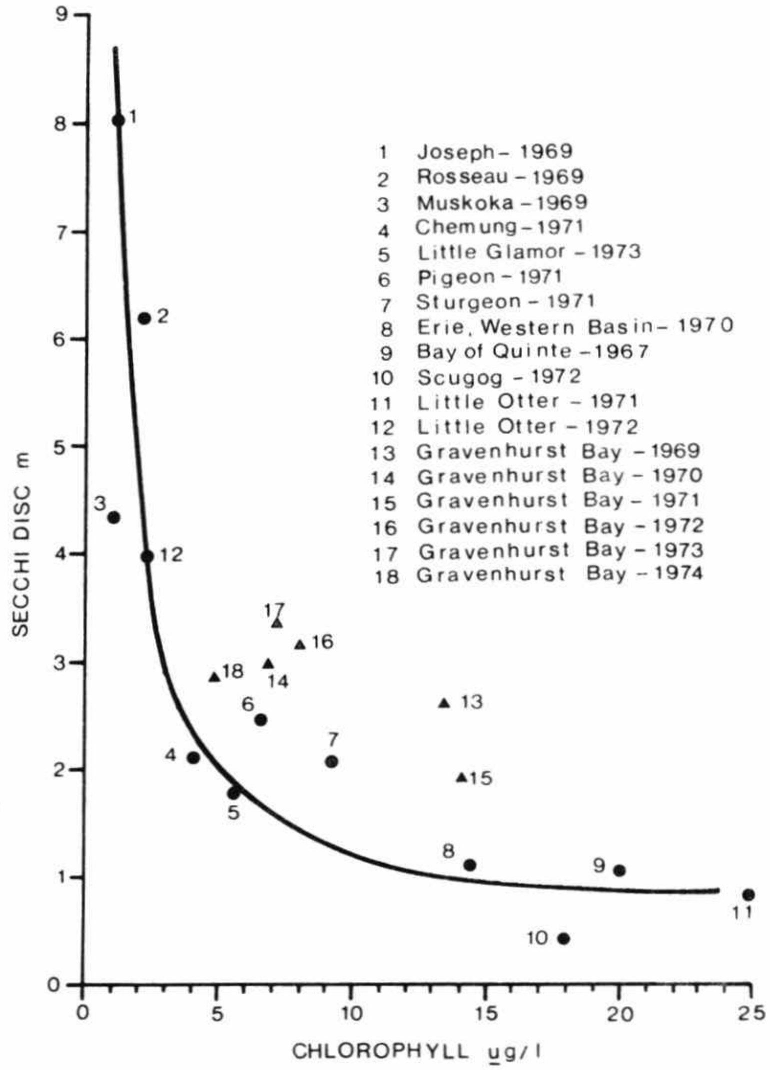

Figure 11: The relationship between chlorophyll $\underline{a}$ and Secchi disc for Gravenhurst Bay 1969-1974 and for other recreational lakes in the Province. All data are ice-free period means.

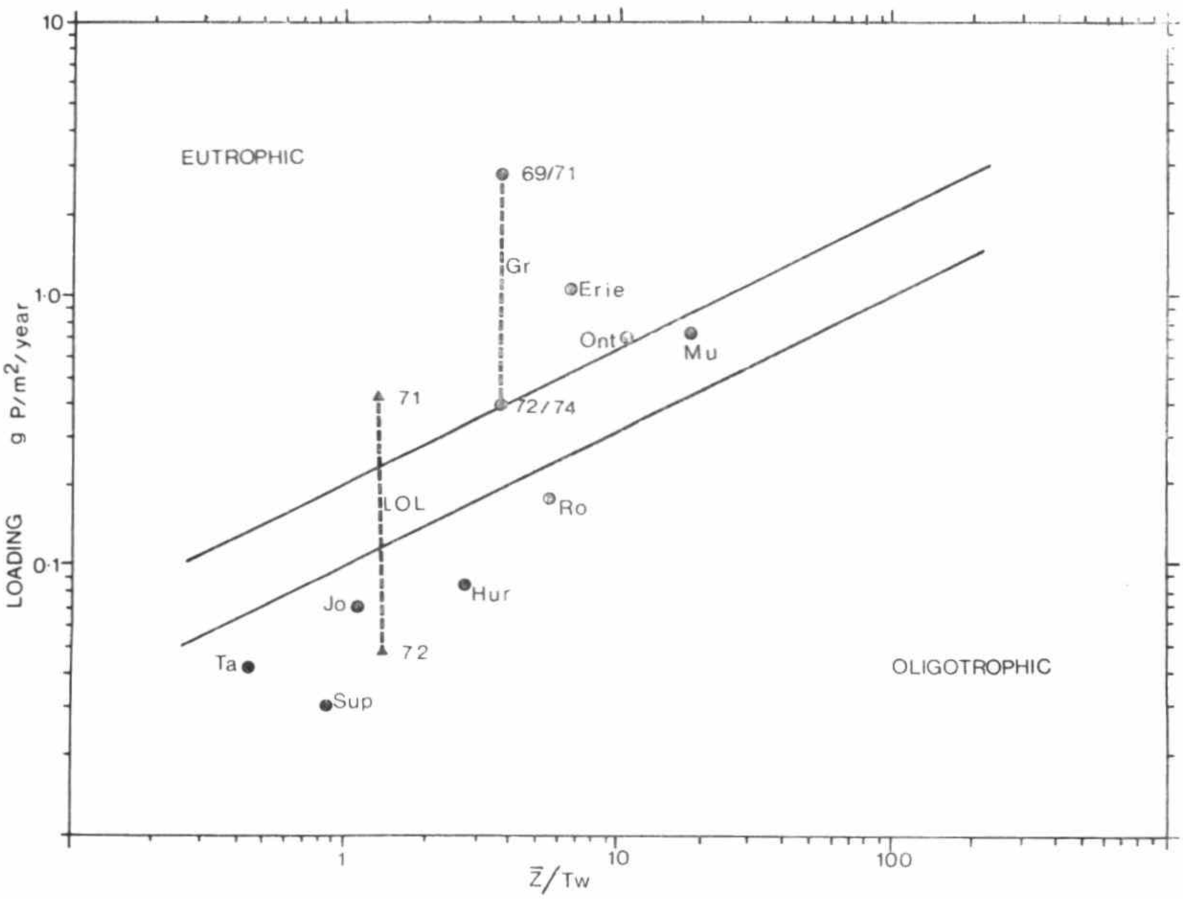

Figure 12: Annual total phosphorus loadings (closed circles) to Ontario Lakes Joseph, Rosseau and Muskoka (after Michalski et al. 1973) and to Lakes Ontario, Erie, Superior, Huron and Tahoe (After Vollenweider 1973). Loading rates and clarification of the degrees of eutrophy (i.e. diagonal lines) are after Vollenweider (1973). Lakes above the upper diagonal are eutrophic in status while lakes below the lower diagonal are oligotrophic. Lakes between the diagonals are mesotrophic. The closed circle "Gr '72/74" represents the "measure of oligotrophication" for Gravenhurst Bay following 90% reduction of phosphorus from the Gravenhurst and Ontario Hospital Sewage Treatment Plants. Closed triangles for Little Otter Lake reflect "before" and "after" phosphorus reductions; improvements to the lake (i.e. as evinced by increased Secchi disc and decreased chlorophyll a) corresponded with changes which would be expected on the basis of Figures 11 and 12.